

SOME PHYSICAL PROCESSES IN DRY SNOW AS SEEN

IN LABORATORY EXPERIMENTS ^{1/}

by

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Introduction

Everyone who has had to deal with snow in any connection whatsoever is well aware that it is an unstable material. Snow is found at temperatures close to its melting point, it has a low viscosity, high porosity and a high vapor pressure. The properties of snow invariably change with time. In addition to the thermodynamic stresses other stresses are imposed by gravitation. It is to be hoped that the reaction of a snow cover to these stresses will someday be predictable and this is, of course, the aim of research in this area.

Recent experiments have been conducted in an attempt to determine the reaction of snow to a particular set of variables, chiefly time and temperature. These experiments, specifically involving the measurement of unconfined compressive strength, have been conducted in the absence of strong temperature gradients and are, therefore, representative of a particular natural environment only. Field work has indicated that this environment is encountered on high polar ice caps and occasionally in deep alpine snow covers.

Previous Investigations

Previous studies, conducted on snow samples, indicated that the compressive strength of snow was a non-linear function of time. The principal source of strength appeared to lie in the bonds between the individual grains and was related to both the number of bonds and to the size of each individual bond. This work has since been supported by investigations on ice spheres brought in contact and allowed to grow together. These latter experiments carried out by Kingery (1960), Kuroiwa (1961) and Hobbs and Mason (1964), have been compared to a similar process known in powder metallurgy as sintering.

Present Studies

Experiments have been conducted in an attempt to determine the nature of the sintering process as it occurs in bulk snow samples. The testing of naturally and artificially compacted snow in unconfined compression has been carried out both in the laboratory and in the field. In the laboratory it is possible to vary both the age of the sample and the temperature with considerable ease. In the field, time, temperature, and density vary with depth and hence, are somewhat controllable by sampling in a vertical profile.

The effects of grain size, shape and crystallographic orientation are less easy to determine and at present require additional study.

Figure 1 shows a typical curve in which the age of the snow is plotted against unconfined compressive strength. In this case, the curve was determined by testing a number of artificially compacted samples which had been allowed to sinter for varying lengths of time. In general there is good density control, within the third decimal place, so that this is not a variable. The compressive strength is determined by placing the samples which are cylindrical in shape, in a motorized press. The strength of the snow at the time of failure is determined by reading a dial gage of a proving ring for which there is a calibration curve of strength vs displacement. Similar tests can be carried out making density, time, temperature, or grain size, the independent variables. On the basis of these tests, the following conclusions can be made.

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Conclusions

In the absence of strong temperature gradients and applied gravitational stresses the tendency of snow is to become stronger with respect to time. This is due to the growth of bonds between the individual grains.

While several mechanisms could be responsible for the growth of bonds it appears most likely that the major mechanism is one of evaporation, diffusion through the environment and condensation. Evaporation occurs on the convex parts of the grains and condensation on the concave region of the bond. This is due to the vapor pressure gradient created by the curvature. Other possible mechanisms could be volume and surface diffusion, however, the rate at which these proceed does not appear rapid enough to account for the sintering process (Hobbs and Mason). Additional evidence is found in the testing of samples immersed in silicone oil (Ramseier and Keeler, 1966). In this experiment the silicone oil prevented the normal evaporation-condensation process and since these samples sintered at a very slow rate (see Figure 2) this is strong evidence for the fact that evaporation-condensation is the dominant process in nature.

The strengthening of snow for samples of constant porosity (constant density), follows a curve which can be fit by an exponential equation

$$\sigma_{\gamma} = \sigma_f [1 - \exp(-K\gamma)] \quad (1)$$

where σ_f is the final unconfined compressive strength, σ_{γ} is the unconfined compressive strength after time γ and k is defined as

$$K = A \exp\left(-\frac{E}{RT}\right) \quad (2)$$

where A and E are constants, E being the activation energy of the sintering process (found by Ramseier and Sander to be $10.2 \text{ Kcal.mole}^{-1}$), R the gas constant, and T the absolute temperature, (Ramseier, 1966).

Time γ is chosen rather than the conventional t because at time $t = 0$ the strength is not zero, but rather has some positive value. It appears from these tests that for artificially compacted samples γ is equal to zero at approximately -6 days. This initial strength is due to bonds created in the compaction of the sample.

The two unknowns are thus A and σ_f . Ballard and McGaw have written an equation for σ_f for fully sintered snow.

$$\sigma_f = \sigma_i \left(1 - \frac{n - n_1}{n_1}\right) \quad (3)$$

where σ_i is the unconfined compressive strength of fine grained randomly oriented, bubble free ice, n is the porosity and n_1 is the limiting porosity. In theory n_1 is the porosity of the sample if one could increase the porosity to the point at which the grains were about to pull away from each other. n_1 is thus a function of snow structure and may vary between 0.5 and 0.6.

σ_i has been found experimentally by Butkovich (1954) to be a function of temperature θ .

$$\sigma_i = 41.83 - 0.788 \theta \quad (4)$$

Thus while the sintering rates are lower for low temperature snows their ultimate strengths will be higher. By the same token reducing the temperature of any snow will result in an increase in strength. This effect can be seen in Figure 3. The constant A is a function of porosity and snow structure and must be found experimentally.

Figure 4 shows some typical sintering curves for samples sintered at various lengths of time and at various temperatures, but crushed at a common temperature. The extreme temperature dependence of the rate can be seen clearly.

Figure 5 shows the effect of varying the porosity. A 10 per cent decrease in porosity will result in an approximate 100 per cent strength increase.

In both figures the exponential relationship between time and strength is apparent. This is at variance with the theory of sintering as outlined by Hobbs and Mason (1964) and with the proposal made by Hobbs (1965). The theory calls for a strength increase proportional to time raised to a power. The deviation between theory and practice as related to snow samples is thought to be due to the formation of new bonds which is not accounted for in the theory which considers only the growth of established bonds. A theoretical paper by Ballard and Feldt (1966) tends to support the importance of considering bond initiation in the beginning stages of sintering.

Other variables have been considered to a much less extent. Figure 6 shows the variation of unconfined compressive strength with grain size. This relationship was predicted by Hobbs and could be due to the increasing rate of sintering with decreasing grain size. Other work has shown opposite results and to fully test this point it will be necessary to test samples which are fully sintered. The effect of shape and crystallographic orientation are not known although it has been suggested that orientation may strongly affect the rate.

Figure 7 is a plot of strength against temperature in which the effect of solar radiation is shown. In this case, it is more than likely that the solar radiation term is by itself not important, but rather is simply a means of raising the actual temperature of the sample. It is estimated that, given the time of year and location, the internal temperature of the sample could be as much as 50°C above the ambient air temperature, thus explaining the more rapid sintering rate. While admittedly incomplete, particularly with respect to structure and grain size, the formulation of Equations 1, 2, 3 and 4 makes it possible to suggest some practical usage of this knowledge.

Applications

In discussing applications it is necessary to consider the natural occurrence of snow. Snow in both the polar regions and in the mountains is initially deposited with a loose structure and very high porosity. Following the initial deposition it may or may not be reworked by wind action which tends to abrade the snow grains and mechanically sort them.

The snow pack then becomes subject to the stresses mentioned in the introduction. In the absence of strong temperature gradients the tendency for thermodynamic equilibrium will result in the formation of bonds and the growth of bonds throughout the snow pack. In the presence of a strong temperature gradient there will be a gross movement of mass resulting in the preferential densification of some layers. This latter process which is of considerable concern in avalanche research occurs frequently in the mountains and occasionally in the polar zones. Experiments have indicated that in the absence of a temperature gradient this will not occur (Kojima, 1961) and that a temperature close to the melting point is required to drive this process to any degree of completion (Giddings and LaChapelle, 1962; de Quervain, 1963). It is generally recognized that in years such as the winter 1964-65 in which the initial snowfalls were heavy that depth hoar does not develop to any extent. This is due to compaction and because the initial temperature gradient tends to be less steep. A USA CRREL field party working in Goose Lake, Montana found that year a very compact, uniform and hard snow pack in comparison to that of the previous year which was marked by depth hoar.

Assuming then that in both the polar regions and occasionally in the mountains, it is possible to have a snow pack in which gross transport of water vapor is not an important factor, one can apply the equations of snow strengthening.

An obvious practical application is in the use of snow for engineering purposes such as the construction of snow roads, runways (Abels, Ramssier, Wuori, 1966) or in the case of the 1960 Squaw Valley Olympic Games, parking lots (Moser, 1963). The equations tell us that the sintering process is strongly temperature dependent, i.e., the sintering rates increase with increasing temperature or vice versa. This would indicate that the time to process snow would be when the temperature was fairly close to the melting point. What knowledge we do have regarding the effect of grain size and shape suggests that a fine grained uniform snow mass tends to sinter faster consequently, we can arrange for the processing of snow to achieve this state. Machines such as the Swiss Peter Snow miller are used in the Antarctic and Greenland to process snow for covering cut trenches in camp

construction and to build snow runways. Given the initial conditions and the weather records it will be possible to predict the length of time which the snow should be sintered before use and the strength it will ultimately have. This knowledge has been used successfully in establishing design criteria for snow runways capable of supporting loads of as much as 100 psi (Abele, Ramseier and Wuori). Another application which would be of considerable interest to people in the Mountain States is the prediction of the strength parameters of a snow cover on potential avalanche slopes. Here again all that is required is a knowledge of such properties of the snow as density, grain size, the ambient air temperature and the climatological history. Given this knowledge it would be possible to utilize the equations to determine both the present strength of the pack and its ultimate strength. Unfortunately, as previously mentioned, temperature gradients and ventilation tend to produce overriding effects which lead to instability.

Conclusions

It is admittedly true that the measurement of unconfined compressive strength is not an ideal test particularly in low density snow, however, it does have the advantage of being simple to perform. It is to be hoped that other strength parameters can also be related to the important variables so that accurate predictions can be made about the state of a snow cover.

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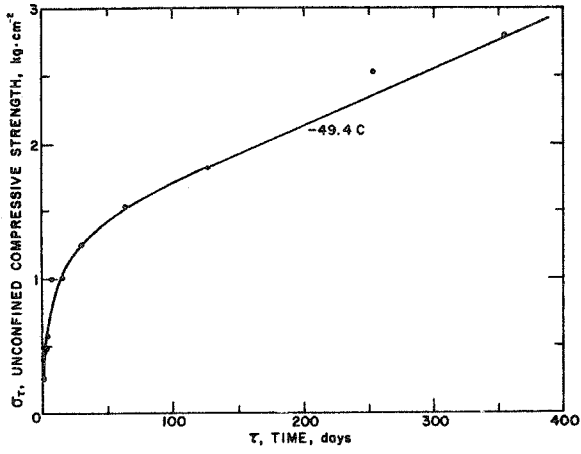


Figure 1. Typical plot of unconfined compressive strength against time. (From Cow and Ramseier).

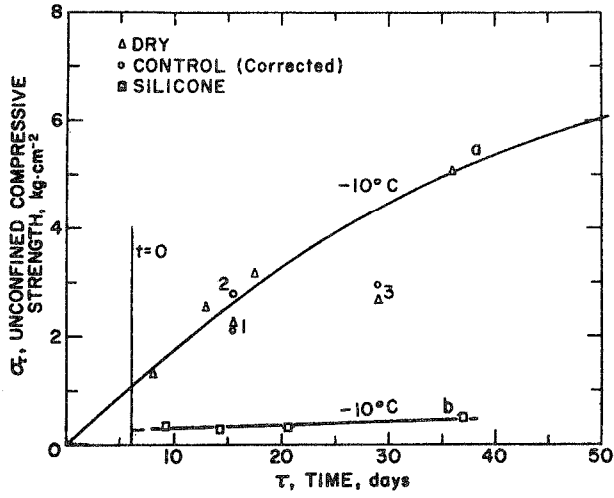


Figure 2. Plot of unconfined compressive strength of time showing curve of samples allowed to sinter in air (curve a.) and curve of samples sintered in silicone oil (curve b.) (from Ramseier and Kaelser).

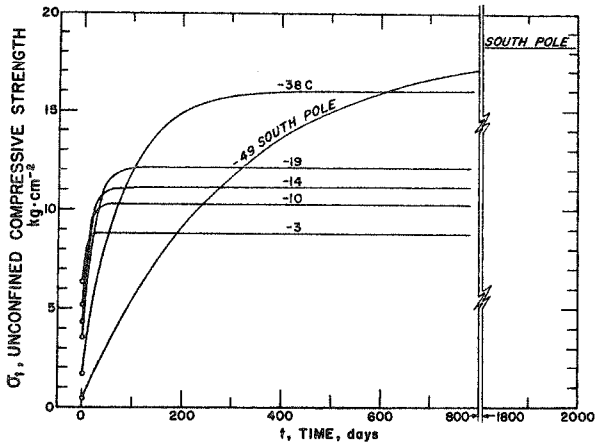


Figure 3. Unconfined compressive strength plotted against time showing the two types of temperature dependence involved.

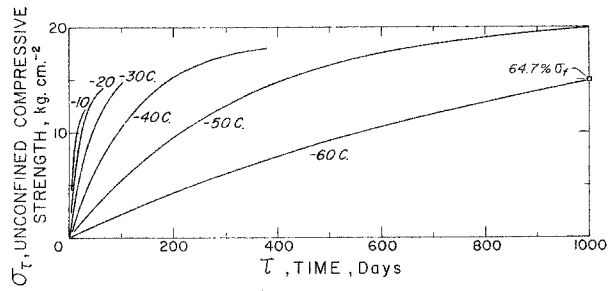


Figure 4. Plot of unconfined compressive strength against time showing effect of temperature on rate of strengthening. (From Ramseier).

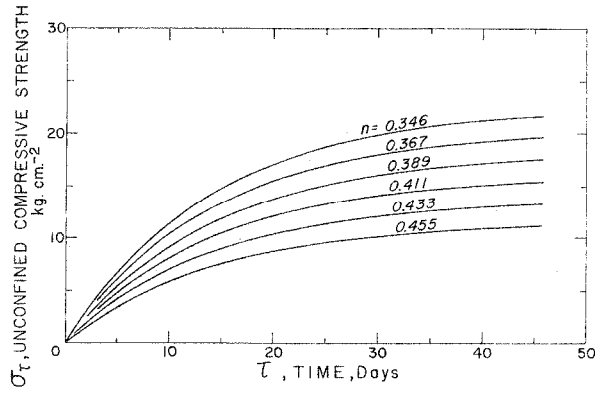


Figure 5. Plot of unconfined compressive strength against time showing the effect of varying porosity. (From Remsler).

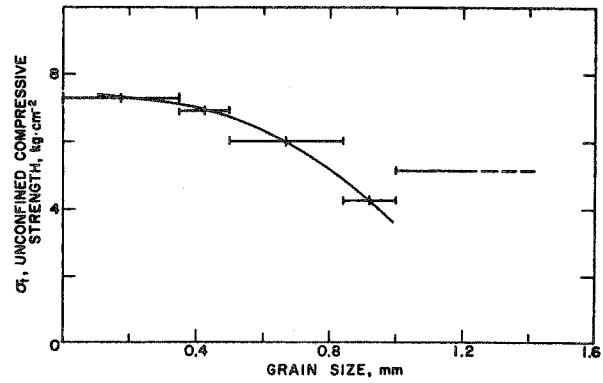


Figure 6. Unconfined compressive strength against grain size. Samples all aged for 165 hours. (From Cow and Remsler).

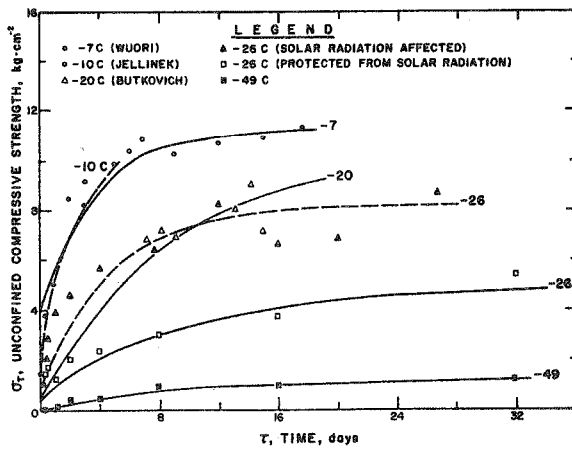


Figure 7. Unconfined compressive strength against time showing the effect of solar radiation. Temperature is ambient air temperature. (From Cow and Remsler).